Humanizing Robots in the Exploration of the Solar System

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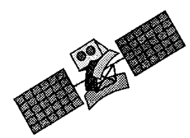
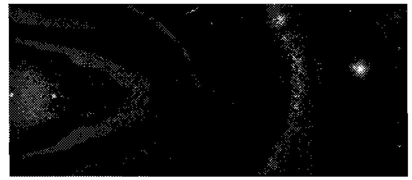


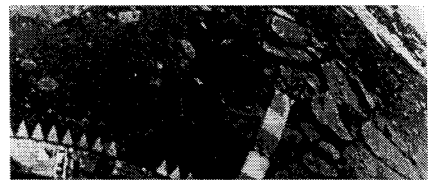
The Future Mission Challenge

Bold New Missions

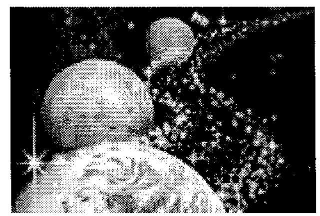
- **Interstellar Exploration**
  - Extreme form of autonomy required, including decades-long survivability, unknown cruise hazards, unknown prioritization of science goals at target.



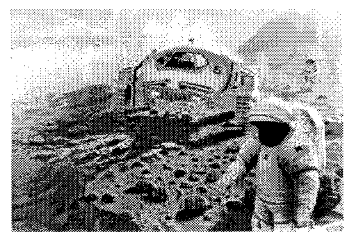
- **Extreme Environments**
  - Some missions will be conducted under highly hazardous and uncertain conditions: cometary surfaces, Venus atmosphere, Europan environment.



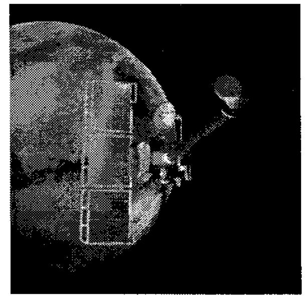
- **Search for Life**
  - Search in some cases will be conducted in environments mostly or completely out of ground communication: Europan ocean?, Titan atmosphere and surface, Mars subsurface.



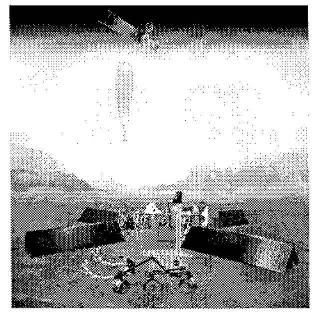
- **Spacesuit Partner (HEDS)**
  - Smart spacesuit which monitors health of occupant and suit status, and can actively assist in rescue operations via a homing response.



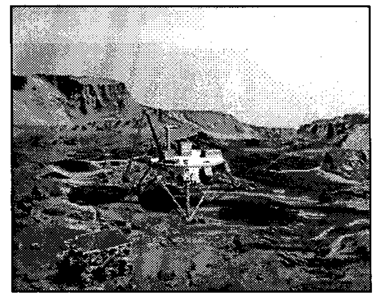
Mars Outposts



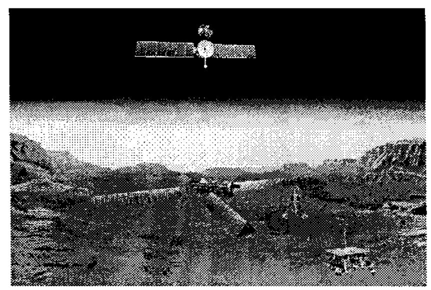
- **Remote Science Laboratories**
  - Tele-operated or autonomous laboratories in the planetary environment for handling and conducting in situ scientific investigations on collected samples



- **Three scales / resolutions**
  - remote sensing
  - distributed sensing
  - point sensing



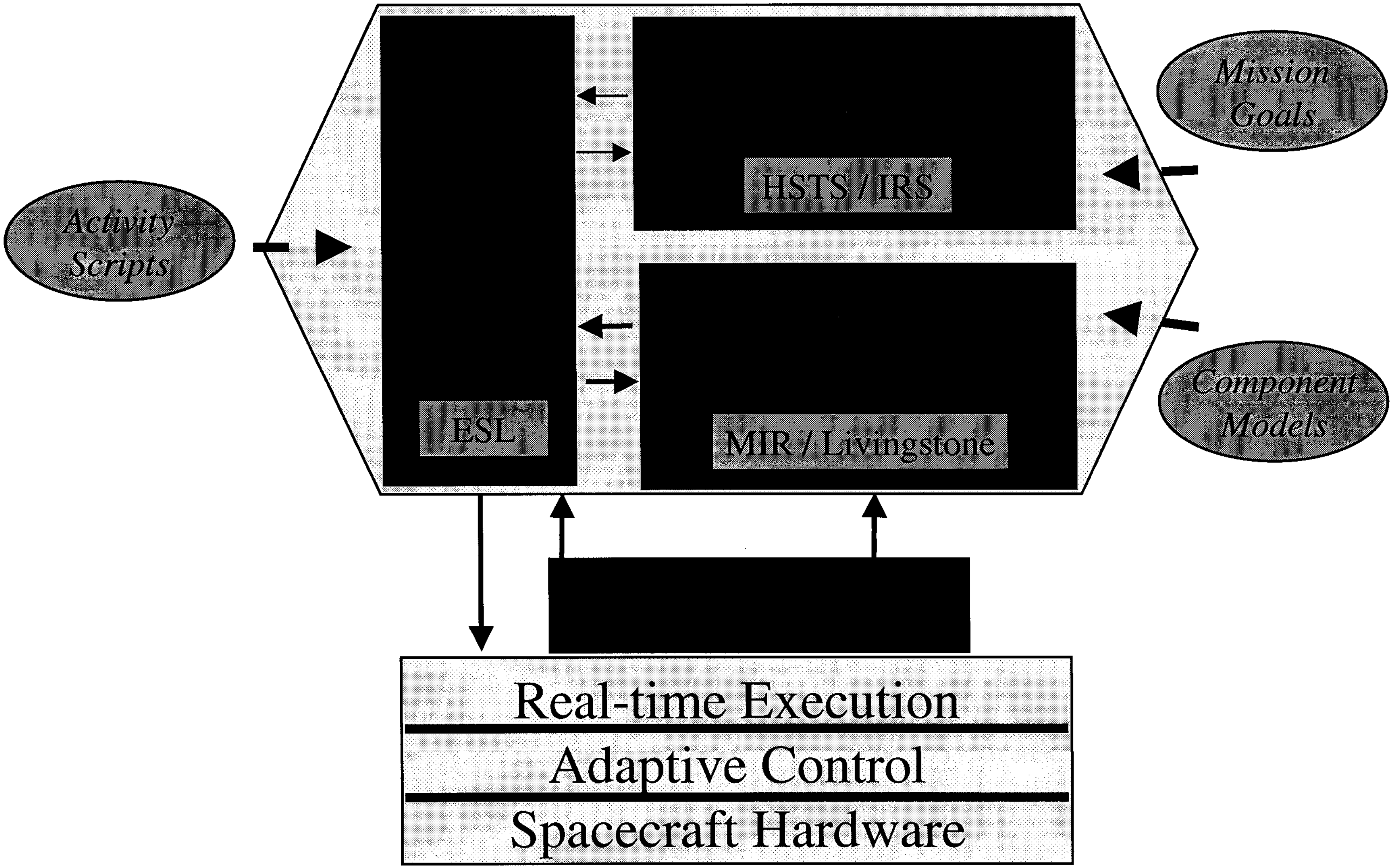
- **Heterogeneous, cooperating networks**
  - distributed networks of sensors, rovers, orbiters, permanent science stations, probes: all of which respond to sensing events, discoveries, changing PI directions, etc., to provide rich presence in Mars environment for science community and public



- **Infrastructure**
  - Planetary permanent infrastructure to support series of science and/or commercial missions leading to human presence

The Emergence of Autonomy

Remote Agent



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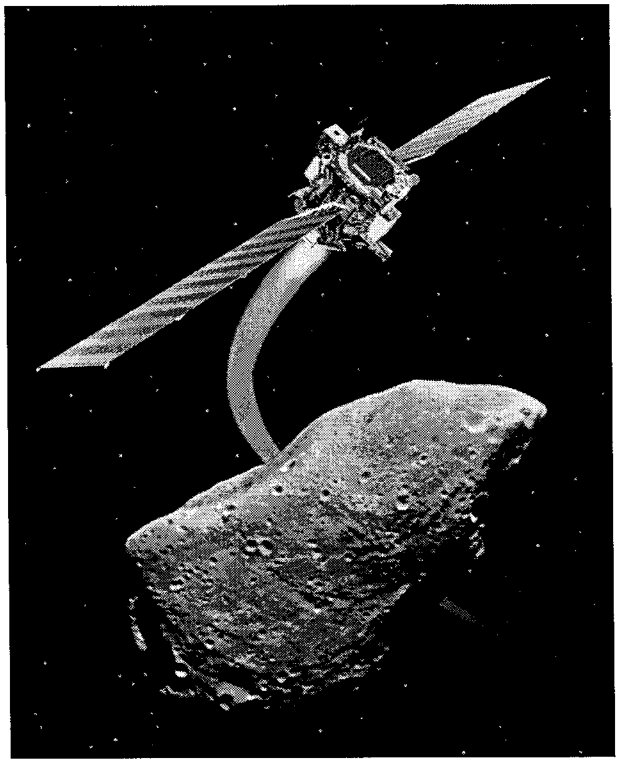
Closing Loops Onboard

Beacon Operations	Ground assistance invoked with focused report on spacecraft context and history
Planner / Scheduler	Re-planning of mission activities around altered resources or functions
Mode Identification & Reconfiguration	Diagnosis of faults and informed selection of recovery actions
Smart Executive	Local retries or alternate, pre-defined activities to achieve same goal
Real-time System	

Several layers of onboard recovery provides for unprecedented robustness in achieving mission goals in the face of uncertainty

New Millennium Flight Experiment



- DS-1 has encountered an asteroid and will encounter a comet.
- Remote Agent Experiment (RAX) achieved 100% of its technology demonstration goals in May ‘99.
- RAX joined 11 other DS-1 technology experiments such as onboard optical navigation and solar electric propulsion.

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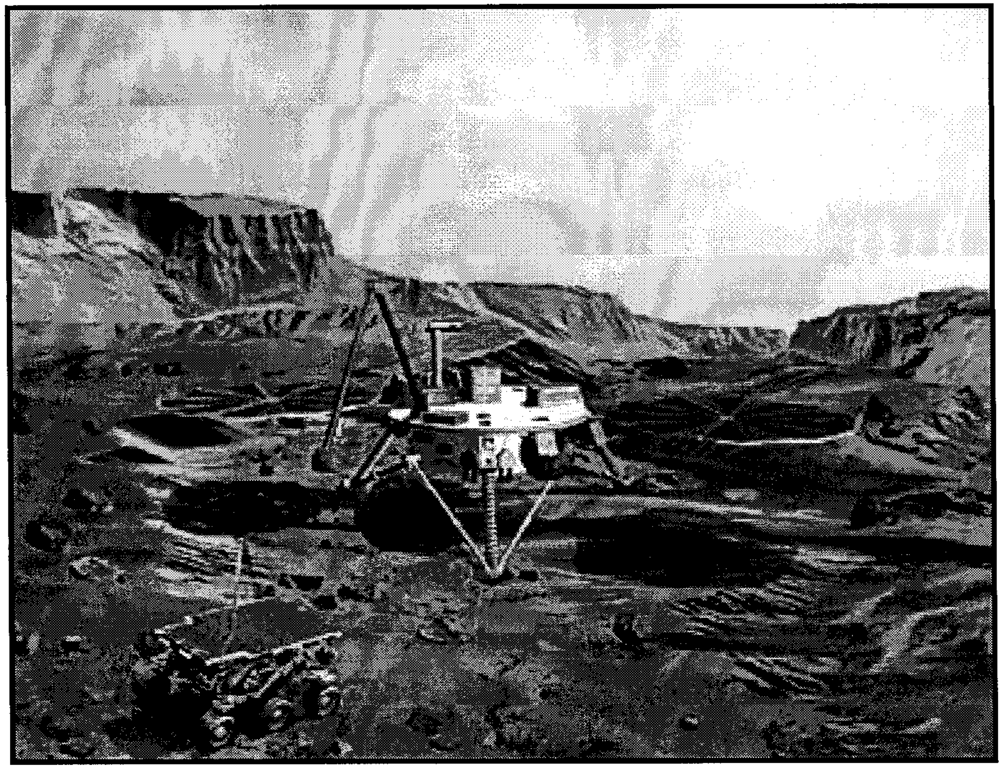
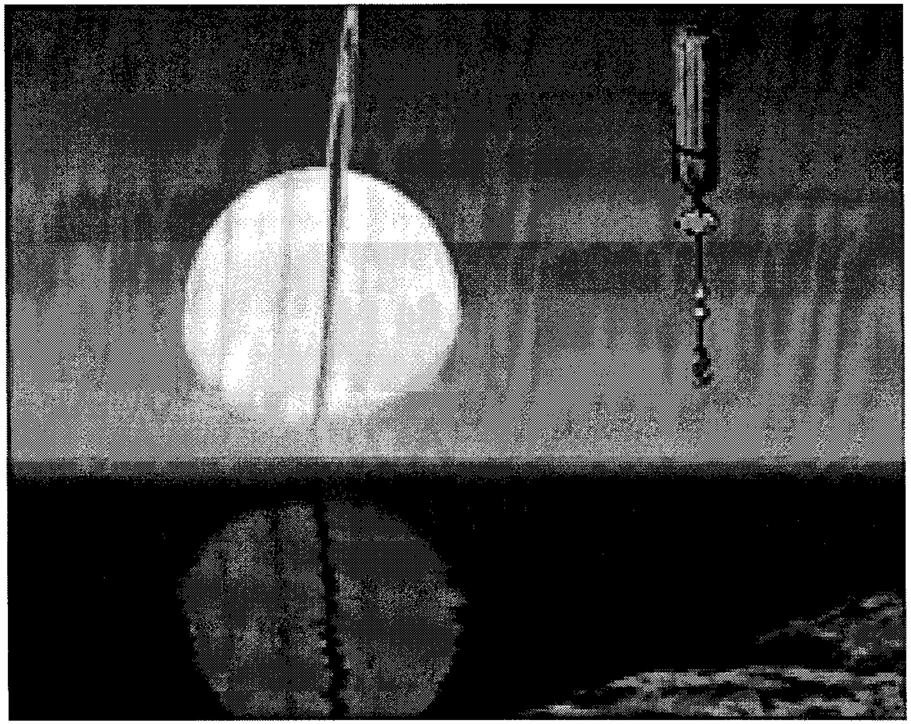
Autonomy for Future Missions

Mars '03 and '05



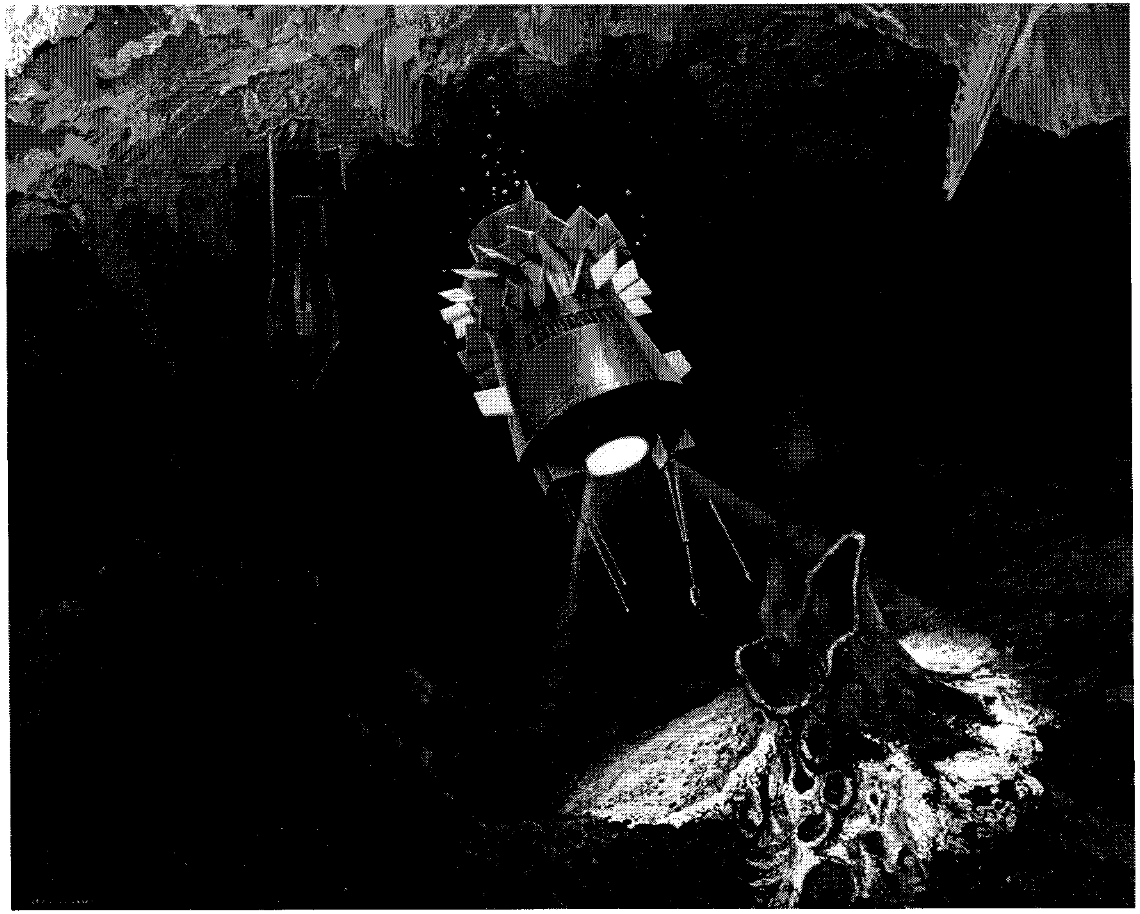
- The Science Team receives an alert from the rover that it has interrupted its traverse to the next science operations site because it has detected an unknown mineralogical signature. The rover has begun initial focused data collection while awaiting instructions.

Titan Aerobot



- The aerobot conducts in-situ science operations when landed, and wide-area imaging when aloft.
- Archived and learned models of wind patterns assist path planning, enabling near-returns to areas of high scientific interest.

Europa Cryobot / Hydrobot



- Perhaps more than any other, a mission of discovery in a truly alien environment: How to know what to look for? How to recognize it?

Looking Further into the Future

Some Definitions

- **Automation**
  - stable functionality for known environment
- **Autonomy**
  - stable functionality for unknown environment
- **Flexibility**
  - evolving functionality for unknown environment

“Flexible” Systems

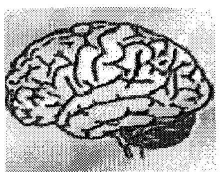
- **Merging of hardware- and software-based capabilities**
- **Concept of phase change in space systems:**
  - Explore functionality space in software
  - “Compile” optimized functionality in hardware
  - Responsive to internal and environmental changes
  - Space system may undergo several “phase changes” over lifetime
- **Take inspiration from biological systems**
- **Key properties of flexible space systems:**
  - Survivability
  - Accomplishment
  - Evolvability

Biological Inspiration for Flexible Systems

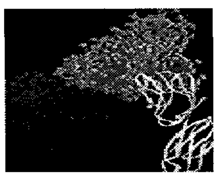
- *Tenacity* - Determined mission continuation no matter what events might occur.

- *Resourcefulness* - Solving problems with whatever means are available.

- *Curiosity* - Deep-seated motivation to explore, investigate and discover.



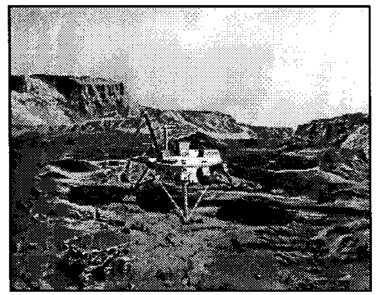
- *Creativity* - Ability to bring fresh viewpoints to bear on problems to be solved and goals to pursue.



- *Evolvability* - Functionality and substructure change over time to meet changing needs.

Theme: Survivability

- Seek space platform lifetime of unprecedented length: a few decades to a century
- Adaptable structures and materials as active offense and defense against environmental uncertainty
- Onboard reasoning capability as extension to hardware redundancy and other forms of fault tolerance
- Achieve mission continuation despite unanticipated and potentially compromising internal or external events

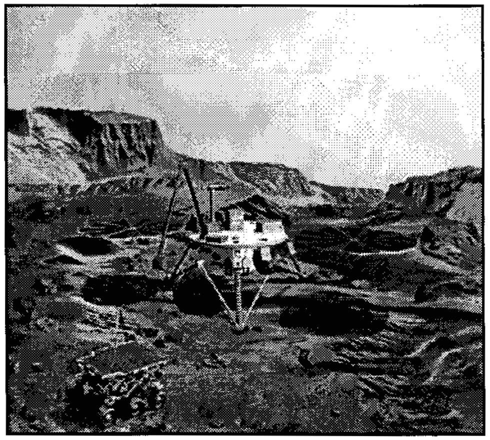


Long-traverse Rover Missions

Phased Capabilities: Survivability

Description

Mission continuation in the face of faults and unanticipated events



5 yrs	Stretch	Out-of-the-Box
Resource management	Hazard detection	*Self-reconfiguration*
Model-based fault protection	Spacecraft skin	*Tool fabrication*
Smart executive	Ultradistributed redundancy	*Self-regeneration*
FPGA - class reconfigurability	In-situ production	*Self-repair*
Extreme envt - certified hw	Social computation	*Self-healing*
Distributed fault tolerance	Morphogenesis	*Immunity-based reliability*

Theme: Accomplishment

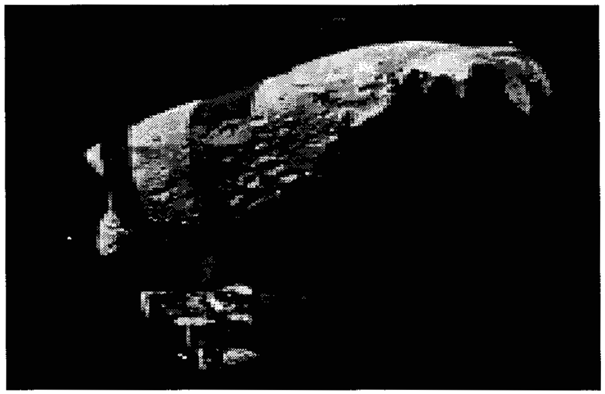
- Perform the mission with zero or extremely infrequent ground support
- Fully self-contained onboard contingency handling and mission (re)planning, closing decision loops in real-time when necessary
- Constantly assess structure and functionality against changing mission goals
- Success no matter what - space system with an attitude

Precision Landing on Small Bodies

Phased Capabilities: Accomplishment

Description

Performing the mission with zero or extremely infrequent ground support



5 yrs	Stretch	Out-of-the-Box
Auto-navigation	Contingency handling	*In-situ utilization*
Auto-maneuvers	Fast onboard re-planning	*Self-fabrication*
Onboard planning	Flexible deployables	*Mind-like architectures*
Sensor nets	Context-dep't functionality	*Self-organization*
Smart instruments	Emotional computation	*Self-replication*
Distributed processors	Ultra low-power systems	*Energy harvesting*
100 Mops / W		

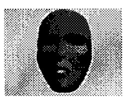
Theme: Evolvability

- Must be able to adapt performance, even structure and functionality, against degradations and changing environmental conditions
- Must exhibit 'surprisability' - assess science and engineering data without explicit models of its content
- "Immunological" responses to environmental conditions
- If existing structure and functionality won't do, change it

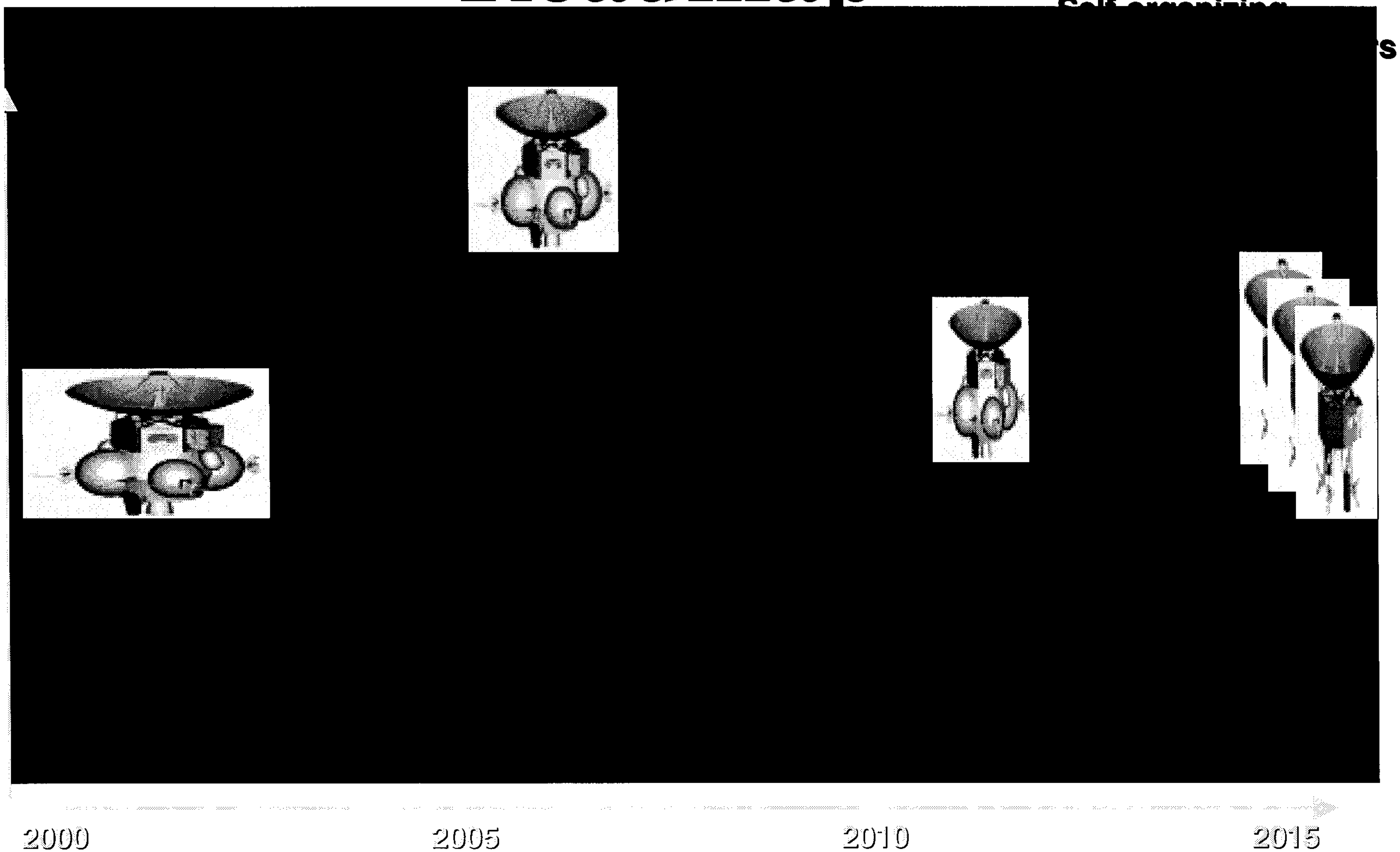
Exploration of Unknowable Environments

Emotional Computation

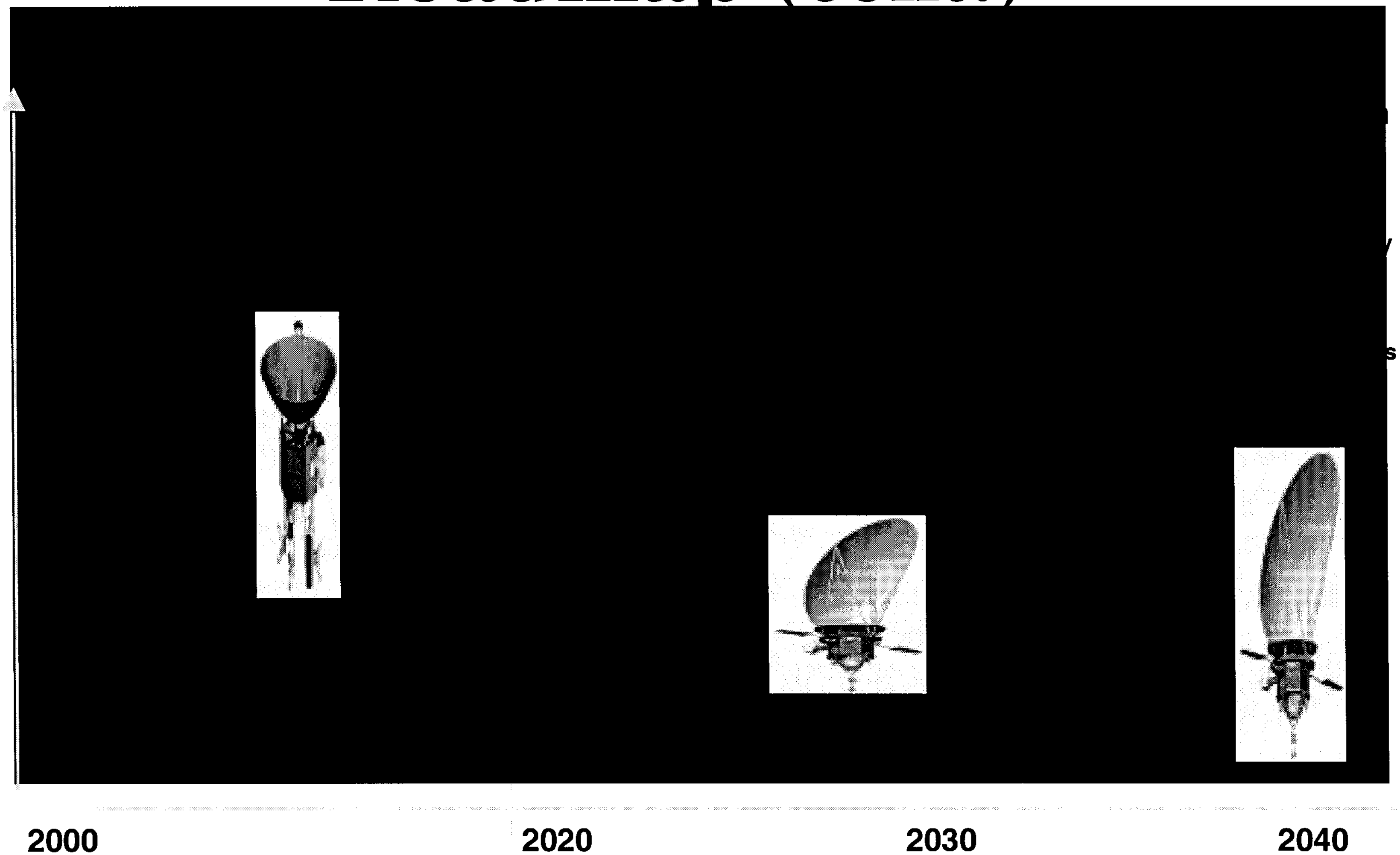
- **Motivation**
  - Emotion as a necessary ingredient in creating human-level problem-solving ability in our space systems
- **Neurological Evidence for Role of Emotion in Decision Making**
  - Brain-injured humans who have had cortex (reasoning center) severed from limbic system (emotional center) exhibit eerily rational behavior: they spend all their time considering one alternative strategy after another without ever deciding on an action
  - When asked to make decisions, human subjects show EEG activity indicating a great deal of communication between cortex and limbic system
- **Possible Mission Applications:**

	Emotion	*Internal State*	*Result*
	**Fear**	**Unacceptable uncertainty in modeling context or environment**	**Locomotion or additional information gathering**
	**Surprise**	**High-level background goal serendipitously achieved**	**Allocate computational resources to attend to event**
	**Boredom**	**Low variance of events and problem-solving activities**	**Trigger agent to dynamically reprioritize tasks**

Autonomy Capability Roadmap



Autonomy Capability Roadmap (cont.)



Summary: The Future of Autonomy and NASA

- NASA is experiencing a return to its most noble goals of exploration, including the search for life.
- Autonomy done well means computer science, spacecraft engineering, mission design, ground systems and operations, software engineering, systems engineering and science expertise must all contribute.
- The design of future autonomous space systems may take inspiration from various successful properties, such as flexibility, of biological systems